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Period-luminosity relations for Galactic Cepheid variables with independent distance measurements.

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ABSTRACT
In this paper, we derive the period-luminosity (PL) relation for Galactic Cepheids with recent independent distance measurements from open cluster, Barnes-Evans surface brightness, interferometry and *HST* astrometry techniques. Our PL relation confirms the results of Tammann et al. (2003), which showed that the Galactic Cepheids follow a different PL relation to their LMC counterparts. Our results also show that the slope of the Galactic PL relation is inconsistent with the LMC slope with more than 95% confidence level. We apply this Galactic PL relation to find the distance to NGC 4258. Our result of $\mu_o = 29.49 \pm 0.06(\text{random error})mag.$ agrees at the $\sim 1.4\sigma$ level with the geometrical distance of $\mu_{geo} = 29.28 \pm 0.15mag.$ from water maser measurements.

Key words: Cepheids – Stars: fundamental parameters

1 INTRODUCTION

Recently, Tammann et al. (2003, hereafter T03) derived the Galactic PL relation by combining the Galactic Cepheids with independent distance measurements from open clusters/associations (Feast 1999) and from the Barnes-Evans (BE) surface brightness techniques (Gieren et al. 1998). The resulting Galactic PL relations in T03 are steeper than the LMC PL relations commonly applied in distance scale applications (as in, e.g., Freedman et al. 2001). Similar conclusions are also reported in Fouqué et al. (2003).

The need to use the Galactic PL relation as a fundamental calibrating relation has become more desirable in recent years (Feast 2003; Fouqué et al. 2003; Kanbur et al. 2003; Tammann et al. 2003; Thim et al. 2003), because of the following two main reasons: (a) The average value of metallicity (defined as $12 + \log[O/H]$) in target galaxies of the H_0 Key Project is $\sim 8.84 \pm 0.31dex$ (Freedman et al. 2001), which is closer to the standard Solar value of $8.87 \pm 0.07dex$ (Grevesse et al. 1996) than the LMC value of $8.50 \pm 0.08dex$ (see reference in Ferrarese et al. 2000); and (b) There is evidence that the LMC PL relation is broken at 10 days (Tammann et al. 2002; Kanbur & Ngeow 2004), i.e., the short (< 10 days) and long period Cepheids in the LMC follow different PL relations. Due to these reasons, the calibrated Galactic PL relation will become important in future distance scale studies.

In this paper, we derive the Galactic PL relation from Cepheids with independent distance measurements. Our analysis of the Galactic PL relation is similar to T03 but different in the following aspects:

(i) In addition to the Cepheids from Feast (1999) and Gieren et al. (1998) that are used in T03, we include other recent distance measurements to Galactic Cepheids that are available in the literature (see Section 2). These include 11 additional Cepheids that are not included in T03.

(ii) As most of the Cepheids we considered here have more than one independent distance measurement, we took the standard weighted-mean of the available distances as the final adopted distance to derive the PL relation.

2 GALACTIC CEPHEIDS WITH INDEPENDENT DISTANCE MEASUREMENT

We collected the Galactic Cepheids with recent distance measurements from the literature, which include:

(i) **Distances from Open Cluster techniques**: These distances are adopted from table 3 of T03, where the authors adopted a distance modulus for the Pleiades of $\mu_{Pleiades} = 5.61 \pm 0.03mag.$ (Stello & Nissen 2001). Feast (1999) estimated that the uncertainty associated with cluster distance moduli is $\sim$ 0.15-0.20$mag.$ (see, e.g., Romeo et al. 1989), hence we assign an uncertainty of 0.20$mag.$ to the open cluster distance moduli ($\mu_o[O.C.]$) in Table 1. This error could incorporate the uncertainty due to the location of the Cepheid in the cluster (far-side vs. near-side), the uncertainty due to metallicity corrections from cluster to cluster,

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etc. (see also Turner & Burke 2002). In addition, we also include other open cluster distances from Turner & Burke (2002) and Hoyle et al. (2003) in Table 1. Since these additional open cluster distances are based on $\mu_{Pleiades} = 5.56mag.$, we add a correction of $+0.05mag$ to these distances[1] in Table 1 to be consistent with the T03 open cluster distances. However, it is unclear whether the distances given in Feast (1999, where the T03 adopted distances originate) and in Turner & Burke (2002) are totally independent to each other or not, since some of them were adopted from the same sources. For example, the open cluster distances for CV MON in Feast (1999) and Turner & Burke (2002) are all adopted from Turner et al. (1998). We have labelled the Turner & Burke (2002) distances that are dubious in this dependency regard in Table 1, and excluded them in obtaining the weighted-mean distances. For GT CAR, CG CAS and TV CMa in Turner & Burke (2002), which are not included in Feast (1999), there is no I band data available in the literature. We exclude them in order to have a consistent number of Cepheids in B, V and I bands.

(ii) **Distances from BE surface brightness techniques**: We adopt these distances from Fouqué et al. (2003), which is an updated version of Gieren et al. (1998), with additional Cepheids that are not included in Gieren et al. (1998). Fouqué (2003, private communication) has verified that the the distances from Gieren et al. (1998) and Fouqué et al. (2003) are not independent of each other, as the distances from the later paper use the latest available data to update the distances in Gieren et al. (1998). The exception is CS VEL, where we include the distance from Gieren et al. (1998) since there is no distance given to this Cepheid in Fouqué et al. (2003). Note that T03 only included the distances from Gieren et al. (1998) but not from Fouqué et al. (2003). We also include the latest distance measurements using BE techniques from Barnes et al. (2003), who used a Bayesian statistical approach in their analysis.

(iii) **Distances from interferometry techniques**: These distances are adopted from Lane et al. (2002), Nordgren et al. (2002) and Kervella et al. (2003). Note that for distances in Kervella et al. (2003), we did not use the direct distance measurements for the four Cepheids (η AQL, W SGR, β DOR & l CAR) because the errors are asymmetric and large (except for l CAR). Instead we adopt the distances from their table 12. These are obtained from combining the interferometry data and the empirical Period-Radius relations from Gieren et al. (1998).

(iv) **Distance from *HST* astrometry techniques**: Currently there is only one Cepheid with a distance measurement from astrometry using the *Hubble Space Telescope*: δ CEP from Benedict et al. (2002).

The selected Galactic Cepheids and the corresponding distances from these sources are summarized in Table 1. Since these distances are from independent measurements, we can take the weighted-mean among the available distances (i.e. column 2, 3, 5 & 6 in Table 1). Note that T03 only uses the distance moduli in column 2 & 4 of Table 1 in their paper. We did not include the distances from *Hipparcos* because the errors in the distance moduli, after conversion from parallax, are large (see, e.g., Madore & Freedman 1998).

In this work, we exclude all the possible non-fundamental mode Cepheids and those not classified as "DCEP" in the General Catalogue of Variable Stars (GCVS, Kholopov et al. 1998). Some of them are mentioned in T03, and include: EV SCT, V1726 CYG, SZ TAU, QZ NOR, α UMi and V367 SCT. We further exclude EU TAU from Barnes et al. (2003) because it is a first-overtone Cepheid. Note that LS PUP is not classified as "DCEP" in the GCVS. We also exclude this Cepheid though it is included in the T03 sample. For Cepheids in Turner & Burke (2002) and Kervella et al. (2003), we did not include the Cepheids that are classified as "DCEPS" in the GCVS, which includes SU CAS, GH CAR and Y OPH. The additional Cepheids included in our sample but not in T03 are labelled in Table 1.

In principle the number of Cepheids can be increased if we include the first overtone (FO) Galactic Cepheids in our sample, by using their fundamental mode periods in obtaining the PL relation. However, we prefer not to include the FO Cepheids due to the following reasons: (a) we want to avoid the contaminations from other types of Cepheids and select only the *bona fide* fundamental mode Cepheids; (b) we want to be consistent with T03, who excluded the non-fundamental mode Cepheids in their study; (c) the physics involved in fundamental mode and FO Cepheids is not the same (see, e.g., Antonello 1994; Antonello & Aikawa 1995; Bono et al. 1999a; Feuchtinger et al. 2000; Bono et al. 2002) and (d) the results of microlensing surveys to the Magellanic Clouds suggest that the FO Cepheids follow their own PL relations (see, e.g., Udalski et al. 1999). The theoretical studies from Bono et al. (1999b) and Baraffe & Alibert (2001) also suggest that the FO Cepheids follow different PL relations. Nevertheless, we list the FO Cepheids (classified as "DCEPS" in the GCVS) with recent distance measurements in Table 2 for completeness. Note that although BD CAS has been updated to "DCEPS" by Poretti (1994), there is no I band data available for this Cepheid in the literature. We therefore exclude BD CAS in Table 2.

3 THE PERIOD-LUMINOSITY RELATION

The values of $\log(P)$, $(B-V)_o$ color, $E(B-V)^2$, and the mean B, V and I band[3] magnitudes for the Cepheids in Table 1 are all taken from T03. The absorption-to-reddening coefficient, R, for individual Cepheids is derived using the prescription given in T03[4]: $R_V = 3.17(\pm0.13) + 0.44[(B-V)_o - 0.78] + 0.05[E(B-V) - 0.42]$, $R_B = R_V + 1.00$ and $R_I = R_V - 1.28$. The B, V and I band extinction-corrected

[1] Thanks to G. A. Tammann for pointing out this correction to Hoyle et al. (2003) distances.

[2] $E(B-V)_{corr}$ in T03.

[3] There are no mean I band values for η AQL, δ CEP and ζ GEM in T03, hence we adopted the I band mean magnitudes from Lanoix et al. (1999).

[4] There are other formulae for the R_V available in the literature. We choose the formula of R_V from T03 in order to be consistent with the work of T03. The detailed study of the sensitivity of PL relation to the selected R_V will be addressed in a future paper.

Table 1. Distances to Galactic fundamental mode Cepheids.

Cepheid (1)	$\mu_o(O.C.)$[a] (2)	$\mu_o(TB)$[a] (3)	$\mu_o(G98)$[a] (4)	$\mu_o(F03)$[a] (5)	$\mu_o(other)$[a] (6)	$\mu_o(w.m.)$[a] (7)
η AQL[i]	···	···	···	6.986 ± 0.052	7.526 ± 0.217[b]; 7.108 ± 0.148[e]	7.025 ± 0.048
RX AUR[i]	···	···	···	···	11.101 ± 0.204[c]	11.101 ± 0.204
U CAR	11.46	11.46 ± 0.04[g]	11.069 ± 0.038	10.972 ± 0.032	···	10.984 ± 0.032
VY CAR	11.63	11.60 ± 0.09[g]	11.419 ± 0.043	11.501 ± 0.022	···	11.503 ± 0.022
WZ CAR	···	···	12.980 ± 0.135	12.918 ± 0.066	···	12.918 ± 0.066
l CAR	···	···	8.941 ± 0.053	8.989 ± 0.032	8.670 ± 0.204[e]	8.981 ± 0.032
CEa CAS	12.69	12.74 ± 0.15	···	···	12.63 ± 0.14[d]	12.662 ± 0.091
CEb CAS	12.69	12.74 ± 0.15	···	···	12.63 ± 0.14[d]	12.662 ± 0.091
CF CAS	12.69	12.74 ± 0.15	···	···	12.63 ± 0.14[d]	12.662 ± 0.091
DL CAS	11.22	11.16 ± 0.04[g]	···	···	10.99 ± 0.14[d]	11.032 ± 0.115
V CEN	9.17	9.16 ± 0.04[g]	9.302 ± 0.024	9.175 ± 0.063	···	9.175 ± 0.060
VW CEN	···	···	13.014 ± 0.042	12.803 ± 0.039	···	12.803 ± 0.039
XX CEN	···	···	10.847 ± 0.065	11.116 ± 0.023	···	11.116 ± 0.023
KN CEN	···	···	12.911 ± 0.060	13.124 ± 0.045	···	13.124 ± 0.045
δ CEP[i]	···	6.76 ± 0.10	···	7.084 ± 0.044	7.173 ± 0.048[b]; 7.181 ± 0.089[f]	7.100 ± 0.029
X CYG[i]	···	10.30 ± 0.05	···	10.421 ± 0.016	10.209 ± 0.055[c]	10.395 ± 0.015
SU CYG[i]	···	9.70 ± 0.06	···	···	···	9.700 ± 0.060
β DOR[i]	···	···	···	···	7.566 ± 0.153[e]	7.566 ± 0.153
ζ GEM[i]	···	7.85 ± 0.10	···	···	7.794 ± 0.228[b]; 7.782 ± 0.211[e]	7.732 ± 0.084
Z LAC[i]	···	···	···	11.637 ± 0.055	···	11.637 ± 0.055
T MON	11.14	11.05 ± 0.14[g]	10.576 ± 0.067	10.777 ± 0.053	10.580 ± 0.068[c]	10.721 ± 0.041
CV MON	11.22	11.12 ± 0.04[g]	10.901 ± 0.046	10.988 ± 0.034	11.39 ± 0.21[d]	11.003 ± 0.033
UU MUS	···	···	12.260 ± 0.092	12.589 ± 0.084	···	12.589 ± 0.084
S NOR	9.85	9.82 ± 0.04[g]	9.918 ± 0.025	9.908 ± 0.032	···	9.907 ± 0.032
U NOR	···	···	10.769 ± 0.067	10.716 ± 0.060	···	10.716 ± 0.060
TW NOR	11.47	11.47 ± 0.08[g]	···	···	11.38 ± 0.18[d]	11.393 ± 0.134
V340 NOR	11.17	11.16 ± 0.11	11.498 ± 0.130	11.145 ± 0.185	11.23 ± 0.12[d]	11.166 ± 0.070
BF OPH	···	···	9.496 ± 0.110	9.271 ± 0.034	9.265 ± 0.192[c]	9.271 ± 0.033
UY PER	11.78	11.88 ± 0.50[g]	···	···	···	11.780 ± 0.200
RS PUP	11.28	···	···	11.622 ± 0.076	11.160 ± 0.290[c]	11.555 ± 0.069
VZ PUP	···	···	13.551 ± 0.036	13.083 ± 0.057	···	13.083 ± 0.057
AQ PUP	···	11.78 ± 0.10	12.750 ± 0.038	12.522 ± 0.045	···	12.397 ± 0.041
BN PUP	···	···	12.924 ± 0.051	12.950 ± 0.050	···	12.950 ± 0.050
GY SGE	12.65	12.74 ± 0.08[g]	12.939 ± 0.071[h]	···	···	12.650 ± 0.200
U SGR	9.07	8.94 ± 0.10[g]	8.869 ± 0.015	8.871 ± 0.022	9.137 ± 0.158[c]; 9.13 ± 0.18[d]	8.881 ± 0.022
W SGR[i]	···	···	···	···	7.933 ± 0.169[e]	7.933 ± 0.169
X SGR[i]	···	···	···	···	7.553 ± 0.161[e]	7.553 ± 0.161
WZ SGR	11.26	11.31 ± 0.04	11.262 ± 0.021	11.287 ± 0.047	12.001 ± 0.169[c]; 11.23 ± 0.16[d]	11.316 ± 0.029
BB SGR	9.11	9.08 ± 0.08[g]	9.238 ± 0.022	9.519 ± 0.028	9.805 ± 0.181[c]	9.518 ± 0.027
RY SCO	···	···	10.469 ± 0.042	10.516 ± 0.034	9.911 ± 0.147[c]	10.485 ± 0.033
KQ SCO	12.36	12.33 ± 0.25[g]	···	···	···	12.360 ± 0.200
RU SCT	11.60	11.64 ± 0.14[g]	···	···	11.41 ± 0.20[d]	11.480 ± 0.141
T VEL	···	···	10.094 ± 0.023	9.802 ± 0.060	···	9.802 ± 0.060
RY VEL	···	···	12.100 ± 0.050	12.019 ± 0.032	···	12.019 ± 0.032
RZ VEL	11.19	11.27 ± 0.31[g]	11.169 ± 0.025	11.020 ± 0.029	···	11.024 ± 0.029
SW VEL	12.08	12.04 ± 0.05[g]	11.989 ± 0.056	11.998 ± 0.025	···	11.999 ± 0.025
CS VEL	12.59	12.59 ± 0.14[g]	12.713 ± 0.144	···	···	12.671 ± 0.117
S VUL	13.24	13.24 ± 0.09[g]	13.731 ± 0.095[h]	···	···	13.240 ± 0.200
T VUL[i]	···	···	···	···	8.920 ± 0.146[c]	8.920 ± 0.146
SV VUL	11.83	11.78 ± 0.05	12.325 ± 0.072[h]	···	11.331 ± 0.081[c]; 10.98 ± 0.21[d]	11.636 ± 0.041

[a] $\mu_o(O.C.)$ = open cluster distance from T03; $\mu_o(TB)$ = open cluster distance from Turner & Burke (2002), adjusted to $\mu_{Pleiades} = 5.61 mag.$ by adding $+0.05 mag.$; $\mu_o(G98)$ = BE distance from Gieren et al. (1998); $\mu_o(F03)$ = BE distance from Fouqué et al. (2003); $\mu_o(other)$ = distance from other sources; $\mu_o(w.m.)$ = the weighted-mean distance for the entries in column 2, 3, 5 & 6, when available. Excepts for CS VEL, which we include the $\mu_o(G98)$ in obtaining the weighted-mean.

[b] Distance measurements from interferometry: η AQL & ζ GEM are from Lane et al. (2002), and δ CEP is from Nordgren et al. (2002).

[c] BE distance measurements from Barnes et al. (2003), who use a Bayesian approach in their analysis.

[d] Open cluster distances from Hoyle et al. (2003), adjusted to $\mu_{Pleiades} = 5.61 mag.$ by adding $+0.05 mag.$

[e] Interferometry distance measurements from Kervella et al. (2003).

[f] *HST* astrometric measurement from Benedict et al. (2002).

[g] These distances are not included in calculating the weighted-mean distances, see text for details.

[h] These distance moduli are not used in both Gieren et al. (1998) and T03 as they appear to be outliers in the PL plots.

[i] These Cepheids are not included in T03.

Table 2. Distances to Galactic first overtone Cepheids.

Cepheid	$\mu_o(O.C.)$[a]	$\mu_o(TB)$[a]	$\mu_o(G98)$[a]	$\mu_o(B03)$[a]	$\mu_o(H03)$[a]	$\mu_o(K03)$[a]	$\mu_o(w.m.)$[a]
GH CAR	···	10.99 ± 0.20	···	···	···	···	10.990 ± 0.200
SU CAS	7.12[c]	7.11 ± 0.03[b]	···	···	···	···	7.120 ± 0.200
V1726 CYG	11.02	11.02 ± 0.03[b]	···	···	···	···	11.020 ± 0.200
QZ NOR	11.17	11.16 ± 0.11	11.095 ± 0.031	···	11.23 ± 0.12	···	11.169 ± 0.075
Y OPH	···	···	···	···	···	9.06 ± 0.21	9.060 ± 0.210
EV SCT	10.92	11.09 ± 0.07	11.066 ± 0.033	···	10.84 ± 0.15	···	11.026 ± 0.060
SZ TAU	8.72	8.71 ± 0.02[b]	8.090 ± 0.042	8.74 ± 0.33	···	···	8.725 ± 0.171
EU TAU	···	···	···	10.27 ± 0.16	···	···	10.270 ± 0.160
α UMi	5.19	5.44 ± 0.05	···	···	···	···	5.425 ± 0.049

[a] $\mu_o(O.C.)$ = open cluster distance from T03; $\mu_o(TB)$ = open cluster from Turner & Burke (2002), adjusted to $\mu_{Pleiades} = 5.61 mag.$ by adding $+0.05 mag.$; $\mu_o(G98)$ = BE distance from Fouqué et al. (2003); $\mu_o(B03)$ = BE distance from Barnes et al. (2003); $\mu_o(H03)$ = open cluster distance from Hoyle et al. (2003), adjusted to $\mu_{Pleiades} = 5.61 mag.$ by adding $+0.05 mag.$; $\mu_o(K03)$ = interferometry distance from Kervella et al. (2003); $\mu_o(w.m.)$ = weighted-mean distances.

[b] These distances are not included in calculating the weighted-mean distances, since it is unclear whether these distances are independent to the distances given in Feast (1999) or T03.

[c] This distance is adopted from Feast (1999), adjusting to $\mu_{Pleiades} = 5.61 mag.$ by adding $+0.04 mag.$

absolute magnitudes for the 50 Cepheids in Table 1 can be calculated by adopting the weighted-mean distance moduli, as given in the last column of Table 1, and then fitted with least-square regressions to obtain the PL relation. The plots of the fitted Galactic PL relations are presented as solid lines in Figure 1, with the following expressions:

$$M_B = -2.594(\pm 0.106)\log(P) - 0.674(\pm 0.123), \sigma = 0.248 \quad (1)$$
$$M_V = -2.999(\pm 0.097)\log(P) - 0.995(\pm 0.112), \sigma = 0.226 \quad (2)$$
$$M_I = -3.303(\pm 0.094)\log(P) - 1.450(\pm 0.108), \sigma = 0.219 \quad (3)$$

The error bars in Figure 1 are obtained from the quadrature sum of the error estimates of distance modulus (given in the last column of Table 1), extinction (adopted from Fernie et al. (1995) database[5]) and mean magnitudes. We assign a conservative error of $0.05 mag.$ to the mean magnitudes. This is reasonable because the mean magnitudes are derived from accurate and reliable light curves (Berdnikov et al. 2000).

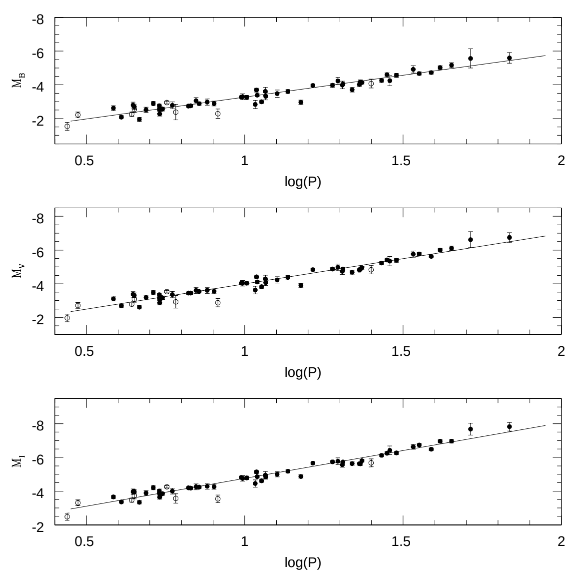

Figure 1. Galactic PL relation in B (top panel), V (middle panel) and I (bottom panel) band. The lines are the fitted PL relations, as given in equation (1)-(3). The solid circles are for fundamental mode Cepheids as listed in Table 1. The open circles are the first overtone Cepheids from Table 2, plotted with their fundamental mode periods. The error bars include the errors in distance modulus, errors in extinction and an error estimation of $0.05 mag.$ in mean magnitudes.

3.1 The effect of FO Cepheids

In this section we investigate the effect of including the Galactic PL relations if we include the FO Cepheids that are listed in Table 2, as suggested by anonymous referee. The fundamental mode periods and the mean magnitudes in B, V and I band for these Cepheids are taken from Berdnikov et al. (2000). The color excess for these Cepheids are calculated via the prescription given in T03: $E(B-V) = 0.951E(B-V)_F$, where $E(B-V)_F$ is taken from Fernie et al. (1995). Then the color, $(B-V)_o$, can be calculated via $(B-V) - E(B-V)$. The extinction corrections for these Cepheids are handled in the same way as in fundamental mode Cepheids. The fitted PL relations from the combination of 59 fundamental mode and first overtone Cepheids are:

$$M_B = -2.590(\pm 0.100)\log(P) - 0.665(\pm 0.111), \sigma = 0.265$$
$$M_V = -3.007(\pm 0.097)\log(P) - 0.962(\pm 0.108), \sigma = 0.257$$
$$M_I = -3.319(\pm 0.098)\log(P) - 1.406(\pm 0.108), \sigma = 0.260$$

By comparing these PL relations to equations (1)-(3), we see that including the FO Cepheids does not significantly alter or improve the PL relations. However, the dispersions of the PL relations (σ) have become larger than the PL relations without FO Cepheids. This is mainly due to the

[5] `http://ddo.astro.utoronto.ca/cepheids.html`

one outlier, GH CAR (with $\log(P_o) \sim 0.91$), as shown in Figure 1. After removing this Cepheid, the dispersions of the PL relations become comparable to those given in equations (1)-(3). Even though the PL relations with the FO Cepheids are almost identical to the PL relations without FO Cepheids, we prefer the solutions given in equations (1)-(3) to be the calibrated Galactic PL relations, as we have argued in Section 2.

3.2 The effect of open cluster distances from Turner & Burke 2002

Since it is unclear whether some of the open cluster distances given in Turner & Burke (2002) are totally independent of the distances given in Feast (1999) or not, we examine the changes of PL relations if we either exclude *all* open cluster distances from Turner & Burke (2002) or assume that these distances are totally independent of Feast (1999), and include them in obtaining the weighted-mean distances. Recall that equations (1)-(3) used some of the Turner & Burke (2002) distances that are either excluded in or independent of Feast (1999). For the former case, the PL relations with 49 fundamental mode Cepheids are:

$$M_B = -2.627(\pm 0.105)\log(P) - 0.623(\pm 0.123), \sigma = 0.240$$
$$M_V = -3.025(\pm 0.096)\log(P) - 0.954(\pm 0.112), \sigma = 0.220$$
$$M_I = -3.320(\pm 0.095)\log(P) - 1.420(\pm 0.110), \sigma = 0.216$$

For the latter case where we include *all* the open cluster distances from Turner & Burke (2002), the fitted PL relations for the 50 Cepheids in Table 1 become:

$$M_B = -2.619(\pm 0.107)\log(P) - 0.656(\pm 0.123), \sigma = 0.249$$
$$M_V = -3.024(\pm 0.097)\log(P) - 0.977(\pm 0.111), \sigma = 0.225$$
$$M_I = -3.328(\pm 0.098)\log(P) - 1.432(\pm 0.108), \sigma = 0.217$$

Therefore, the exclusion or inclusion of Turner & Burke (2002) distances produces almost identical PL relations. These PL relations also agree and are consistent with equations (1)-(3). However, there are some open cluster distances that are not included in Feast (1999) or T03 (e.g. for Cepheid AQ PUP), and there are certain cases where we have confidence to believe that the distances given in Turner & Burke (2002) and Feast (1999) are independent (e.g. for Cepheids CEa, CEb and CF CAS). Hence we continue to adopt equations (1)-(3) as the calibrated Galactic PL relations.

4 COMPARISON TO PUBLISHED RESULTS

4.1 Comparison to other Galactic PL relations

We selected recent empirical PL relations from the literature that give *both* V and I band PL relations to be compared with our results, because the PL relations in these two bands are extensively used in extragalactic distance scale studies (e.g., Freedman et al. 2001). For example, we exclude the PL relations from Barnes et al. (2003) or Hoyle et al. (2003) because they did not give the I band PL relations in their papers. The selected PL relations, along with our results, are given in Table 3. These include the Galactic PL relations derived by Gieren et al. (1998, GAL-G98), Fouqué et al. (2003, GAL-F03) and Tammann et al. (2003, GAL-T03). We exclude the *Hipparcos*-based Galactic PL relations because these PL relations adopted the slopes from LMC PL relations, and calibrated the zero-points with *Hipparcos* data (as those used in, e.g., Lanoix et al. 1999 and Paturel et al. 2002). From the table, it can be seen that our results are consistent with the GAL-G98 and GAL-F03 PL relation. However there is some discrepancy between our results and GAL-T03. In this situation, we can use the t-statistical test (see, e.g., Zwillinger & Kokoska 2000) to assess the significance of the difference in slopes under the null hypothesis that the slopes are the same. The results show that the p-value for the V and I band slopes are 0.15 and 0.27, respectively. Hence the null hypothesis cannot be ruled out at the 95% confidence level, and our results are also consistent with the GAL-T03 PL relation.

The small discrepancy of the PL slopes between our results and T03 is mainly due to the inclusion of additional distance measurements in this work (see Section 2 for details). If we take the arithmetic, unweighted-mean of the 39 Cepheids with $\mu_o(O.C.)$ and $\mu_o(G98)$ in Table 1 (as these distance moduli are used in T03), the slopes of the fitted PL relations become steeper: $a_B = -2.750 \pm 0.123$, $a_V = -3.130 \pm 0.110$ and $a_I = -3.402 \pm 0.106$, which agree with the results of T03. However, by taking the weighted-mean distances for these 39 Cepheids, the PL slopes become shallower but still consistent with T03: $a_B = -2.721 \pm 0.125$, $a_V = -3.102 \pm 0.112$ and $a_I = -3.373 \pm 0.109$. Thus the different between our results and T03 is due to the inclusion of additional distance measurements in our study.

For completeness, we also include the recent theoretical PL relations in Table 3 from Baraffe & Alibert (2001, GAL-Theory1) and Fiorentino et al. (2002, GAL-Theory2 & GAL-Theory3) by adopting $Z = 0.02$. From the table, our empirical PL relations fairly agree with the theoretical PL relations from Baraffe & Alibert (2001). However, none of the empirical PL relations given in Table 3 agree with the GAL-Theory2 and GAL-Theory3.

4.2 Comparison to LMC PL relation

Since the PL relation is shown to be different in the LMC and Galaxy by T03 (also in Fouqué et al. 2003 and Kanbur et al. 2003), we verify this result by comparing our Galactic PL relation to the LMC counterpart, as given in Freedman et al. (2001). For our Galactic PL relation, the difference in the V and I band slopes is: $\Delta a_V = 0.239 \pm 0.102$ and $\Delta a_I = 0.341 \pm 0.096$, which are 2.3σ and 3.6σ results, respectively. We also apply the t-statistical test to test for the equality in the slopes of the Galactic and LMC PL relation. The results show that the slopes in the Galactic and LMC PL relation are inconsistent at more than a 95% confidence level, with p-value of 0.017 and 0.001 for the V and I band slopes, respectively. Therefore, Cepheids in the Galaxy and the LMC do follow different PL relations, and hence the Cepheid PL relation is not universal.

Table 3. Comparison of various PL relations[a].

PL relation	N	a_V	b_V	σ_V	a_I	b_I	σ_I	Ref.[b]
GAL-G98	28	-3.037 ± 0.138	-1.021 ± 0.040	0.209	-3.329 ± 0.132	-1.435 ± 0.037	0.194	1
GAL-F03	32	-3.06 ± 0.11	-0.989 ± 0.034	···	-3.24 ± 0.11	-1.550 ± 0.034	···	2
GAL-T03	53	-3.141 ± 0.100	-0.826 ± 0.119	0.24	-3.408 ± 0.095	-1.325 ± 0.114	0.23	3
GAL-Here	50	-2.999 ± 0.097	-0.995 ± 0.112	0.226	-3.303 ± 0.094	-1.450 ± 0.108	0.219	4
GAL-Theory1	···	-2.905	-1.183	···	-3.102	-1.805	···	5
GAL-Theory2	···	-2.45 ± 0.02	-1.50 ± 0.02	0.17	-2.78 ± 0.01	-2.02 ± 0.01	0.13	6
GAL-Theory3	···	-2.22 ± 0.01	-1.62 ± 0.01	0.14	-2.58 ± 0.01	-2.14 ± 0.01	0.10	7
LMC	~ 650	-2.760 ± 0.030	-1.458 ± 0.020	0.160	-2.962 ± 0.020	-1.942 ± 0.010	0.110	8

[a] $M_{V,I} = a_{V,I} \log(P) + b_{V,I}$, and $\sigma_{V,I}$ is the rms dispersion. For LMC PL relation, assume $\mu_{LMC} = 18.50 mag$.

[b] Reference: [1] Gieren et al. (1998); [2] Fouqué et al. (2003); [3] Tammann et al. (2003); [4] Equations (2) & (3) from this work; [5] Baraffe & Alibert (2001), with $Z = 0.02$; [6] table 6 from Fiorentino et al. (2002), with $Y = 0.31$ and $Z = 0.02$; [7] table 6 from Fiorentino et al. (2002), with $Y = 0.28$ and $Z = 0.02$; [8] Freedman et al. (2001).

5 THE DISTANCE TO NGC 4258

The Galactic PL relation presented in the previous section can be used to find the distance to NGC 4258, because the metallicity in this galaxy is $8.85 \pm 0.06 dex$ (see reference in Newman et al. 2001), which is closer to the Solar value. Furthermore, there is an accurate geometrical distance measurement to NGC 4258 using the water maser in the inner disk of this galaxy (Herrnstein et al. 1999). The measured geometrical distance is $7.2 \pm 0.5 Mpc$, corresponding to $\mu_{geo} = 29.28 \pm 0.15 mag$.

There are 15 Cepheids discovered with *HST* observations by Newman et al. (2001), where we adopted the periods and the mean V and I band magnitudes (from ALLFRAME photometry) for these Cepheids. The distance modulus to NGC 4258 can be obtained using the prescription given by Kanbur et al. (2003). We did not include the metallicity correction because it is small (Kanbur et al. 2003). The results are given in Table 4, using the different PL relations in Table 3. This shows that the distance to NGC 4258 is consistent with these different empirical Galactic PL relations. However, the distance modulus of $29.49 mag$. (from the PL relations given in equations [2] & [3]), and the median distance modulus of $29.46 mag$. (from the four empirical Galactic PL relations) is still $\sim 1.4\sigma$ and $\sim 1.2\sigma$, respectively, away from the water maser distance[6]. Furthermore, all the theoretical PL relations in Table 3 give a further and inconsistent distance modulus as compared to the distance moduli obtained from empirical PL relations (see, however, Caputo et al. 2002 for a way to resolve this discrepancy). This could be due, in part, to the small number of Cepheids discovered in NGC 4258 (Newman et al. 2001). The on-going Cycle 12 *HST* observations of NGC 4258 (Program ID: 9810; P.I.: L. Greenhill) that proposed to discover ~ 100 Cepheids in this galaxy would help to solve the discrepancy between the Cepheid distance and water maser distance.

[6] Using the mean magnitudes derived in Kanbur et al. (2003) for these 15 Cepheids decreases the μ_o in Table 4 by $\sim 0.06 mag.$, with a median distance modulus of $29.40 mag$.

Table 4. Distances to NGC 4258 with different PL relations[a].

PL Relation	μ_V	μ_I	μ_o
GAL-G98	29.80 ± 0.07	29.65 ± 0.05	29.43 ± 0.06
GAL-F03	29.79 ± 0.07	29.66 ± 0.05	29.46 ± 0.06
GAL-T03	29.73 ± 0.07	29.63 ± 0.05	29.50 ± 0.06
GAL-Here	29.72 ± 0.07	29.63 ± 0.05	29.49 ± 0.06
GAL-Theory1	29.80 ± 0.07	29.74 ± 0.05	29.66 ± 0.06
GAL-Theory2	29.57 ± 0.06	29.58 ± 0.04	29.57 ± 0.06
GAL-Theory3	29.41 ± 0.06	29.45 ± 0.04	29.50 ± 0.06
LMC	29.90 ± 0.07	29.71 ± 0.05	29.44 ± 0.06[b]

[a] The errors are random error only. The systematic error is about $0.15 mag$ (Newman et al. 2001).

[b] The metallicity correction using the LMC PL relation to this galaxy is $\delta_z = +0.07 mag$. (Freedman et al. 2001; Newman et al. 2001). Then the metallicity-corrected distance modulus becomes $29.51 \pm 0.06 mag$.

6 CONCLUSION

By using the recent independent distance measurements to 50 Galactic Cepheids, we derive a Galactic PL relation in the B, V and I bands. Our analysis differs from that in T03 due to the following aspects: (a) we include other recent independent distance measurements; and (b) we took the weighted-mean to the available distances. The results confirm that the Galactic PL relations are steeper than the LMC counterparts (Fouqué et al. 2003; Tammann et al. 2003). However, the steepness of the Galactic PL relation is still inconclusive (either as steep as in T03 or as shallow as in this study) because of the small number (~ 50) of Cepheids in the sample. Application of the Galactic PL relation from equation (2) & (3) to determine the distance to NGC 4258 shows that there is still a $\sim 1.4\sigma$ discrepancy in distance with the water maser measurements. The Galactic PL relation can be improved if there are more independent distance measurements to Galactic Cepheids in the future, such as the Cycle 12 *HST* observations of the nearby Cepheids with astrometric measurements (10 Cepheids from Program 9879, with P.I.: G. F. Benedict, where 3 of them are not included

in Table 1 [Benedict 2003, private communication]) or the future Space Interferometry Mission (SIM, launch in 2009)[7].

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